Technology White Paper

Leapfrogging vs. Pre-Defined Reference Targets

Executive Summary

Move Device Position, or "Leapfrog," is a technique used with portable measuring devices to extend their working volume. Reference points are measured with the device in one position, and then re-measured after the device has been relocated to a new position. The reference points link the new device position with the original coordinate system, allowing for measurements to be taken and reported in the same reference frame.

A pre-defined target reference system consists of a calibrated artifact or set of references that are used for relocation. The position of these targets is established by a separate device capable of large volume measurements, we'll call this the "referencing" device (i.e., a laser tracker). Another measurement device, which we'll refer to as the "inspection" device (i.e., a measurement arm, etc), can be placed anywhere within reach or line of sight of the pre-defined targets and can locate itself inside the larger reference frame by simply measuring any set of reference points.

Overview

In software terms, leapfrogging is simply an iterative — or best fit — alignment of a set of data points measured from different positions. These are tied together in a common coordinate system after moving or "leapfrogging" the device over the reference points and while retaining its relationship to the global coordinate system.

When establishing an alignment between the device and the part, you can expect your measurements to be as good as the actual part is in reference to its nominal value, plus or minus the accuracy of the inspection device.

One "leapfrog" is equivalent to iteratively aligning to your original measurements. Two or more leapfrogs, which rely on different sets of references, can introduce a "stack-up" error.

The amount of error introduced is difficult to estimate as it is the result of a 3D best fit. Depending on how many features are used, the distance between features, and how many times the device is moved using different reference points, you can end up with hundreds or even thousands of compounding error possibilities in any direction.

This means that it is plausible to have a compounded error after a move and have the error cancel itself out after the next move.

Embedded Target Grid

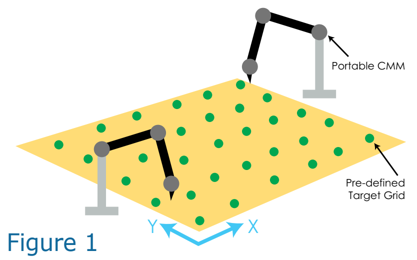


Figure 1

One alternative method of extending the working volume of portable CMMs consists of an asymmetrical grid of conical sockets that are fixed or embedded onto the floor or surface plate of an inspection room (see figure 1). The location of these sockets is mapped via the use of a referencing device (laser tracker). This virtual map is used in conjunction with the measurement software to find the exact location of the inspection device, in this case a portable measurement arm. A minimum of three sockets needs to be within reach of the inspection device in order for it to position itself inside the larger reference envelope. The asymmetry of the grid is used to create unique references that the software can easily recognize. This is achieved by making sure the spacing between any three given points is not the same. Basically, any set of reference points measured corresponds to a unique location on the grid.

Aligning to predefined targets can be seen as being faster and more convenient than leapfrogging, but your measurements are only as good as the actual part, plus or minus the accuracy of the inspection device.

In this scenario you also experience the combined error of the referencing device and the inspection device. Theoretically, this setup eliminates the possibility of compounding errors because each re-alignment is independent of the previous one. It is like performing a series of single leapfrogs.

Pros

This type of system allows users to quickly place a large part over the grid, align to it, and easily inspect areas that are outside the reach of the inspection device by moving it around the grid and using any three reference points to link it back to the global coordinate systems.

The grid requires a onetime setup and can be customized to the desired size.

Cons

This system can become very expensive, not only to install but to maintain as well. It requires a dedicated area which eliminates the portability advantage and needs periodic calibration/re-mapping of the reference points to maintain repeatability. Also, you always start with the uncertainty of the referencing device and then add the uncertainty of the inspection device.

There are several factors that can contribute to accuracy degradation:

- Accuracy of referencing device (tracker)
- Accuracy of the inspection device (measurement arm)
- Stability and stiffness of the measurement device mount (stand)
- Conical socket drift/deformation due to:
    1. Size of the grid — The larger the grid, the less accurate the mapping
    2. Temperature changes — Especially in areas with significant seasonal differences (i.e., very hot summers or very cold winters)
    3. Atmospheric pressure — Large objects, especially near coastal areas, can be affected by the pressure of incoming tides
    4. Continuous floor settling — The ground is always moving
    5. Vibration — Proximity to operating machinery
    6. Loading — Weight of parts, proximity to load bearing walls or heavy traffic

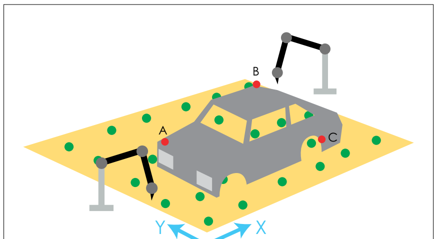


Figure 2

To illustrate how the system works, we'll look at the following scenario. Let's say that you reference a large target grid with a device that is +/- 25µm; then measure three of the references targets with a device that has a repeatability of +/- 50µm. For features measured within the working volume of the inspection device, like feature "A" (see figure 2), you now have a potential compounded repeatability error of +/- 75µm. Now move to another location within the grid and you have the same situation with the same potential maximum error when measuring something like feature "B". Technically, there is no additional loss for measurements taken at any given device position. But, when you compare the relationship between measurements from one device position to another (i.e., A to B), you could see an error that can be two times greater; in this case +/-150µm. This error wouldn't be incremental as more device positions are introduced. Basically if feature "C" was required, the maximum possible error would remain consistent from A to B, A to C, or B to C.

Tetrahedron

Another method used by some providers to extend working volumes is with the use of a tetrahedral or "pyramid-like" artifact that acts similarly to a grid. It has the advantage of being portable, but has a limited range.

A tetrahedron is a 3D object that has four corners and four triangular faces.

This artifact has one sphere in each corner of the four-sided pyramid and the distance between them is known and assumed to be perfect. You create a reference by measuring the three spheres that make up one of the four faces (see figure 3).

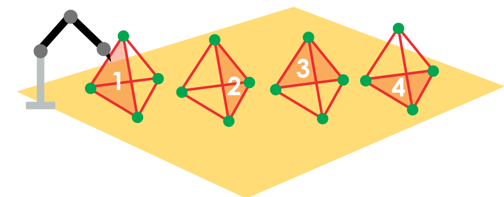
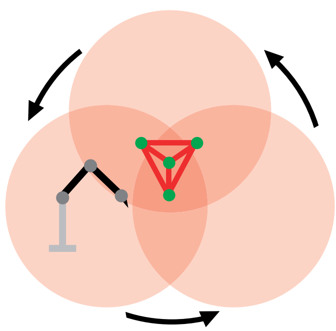


Figure 3

Afterwards, you can relocate your inspection device by moving around the tetrahedron and measuring the spheres that make up any of other faces. The relationship between all spheres has been pre-defined and is assumed constant.

Pros

Figure 4


When properly used, this artifact can increase the working volume of the measurement device approximately 2.5 times. Figure 4 illustrates from a top view how the working envelope of the device has to accommodate three spheres that make one face of the tetrahedron (two corners and the center) and the total area that would be covered after two device moves.

Accuracy loss would be theoretically less than using a large grid-type system because as you change positions, you always have two spheres in common so most of the error would be introduced by the uncertainty of the third one.

The device is portable and can be easily disassembled.

Cons

Even with two common spheres between device moves, you still have a larger uncertainty introduced by the third sphere which is assumed to be perfect relative to the nominal configuration of the tetrahedron.

You only benefit from using three out of the four faces, because measuring the face at the bottom would defeat the purpose of using the artifact.

There are several other factors that can contribute to accuracy degradation with this device:

- Accuracy of the measurement device
- Deformation of the tetrahedron due to:
    1. Temperature — how multiple materials (tubes and spheres) are affected by temperature
    2. Tube stiffness — how rigid the device is
    3. Probing force — how hard an operator press against it
    4. Assembly and disassembly — how repeatable it is after it has been taken apart

5. Spacing between spheres — the closer the spheres are, the higher the potential error
6. Fixture method — how it is clamped or attached to keep from moving when used

Best Practices

There are several techniques you can use to minimize error when moving or relocating a portable measurement device to extend its working envelope:

Maximize the distance between reference targets — the farther apart the reference points are, the more you reduce the chance of incremental error due to angular deviation of the best fit features.

Minimize the distance between device moves — Move only the necessary amount to allow you to comfortably reach the desired features. Any error introduced by angular deviation of the features used to relocate the device, will be higher and more evident the farther away you get from those features.

NOTE: To understand the effects of angular deviation, let's look at figure 5. The red dots represent your measured reference points and the green dots represent your measured reference points after leapfrog. The green dots will have relatively the same position and orientation to each other as the red dots. The composite image illustrates what could happen after re-alignment. Each green dot is affected by the uncertainty of the device used. When they are best fitted together, you can end up with a slight angular shift. This will generate an incremental error as you take measurements away from the references. Increasing the spacing between points reduces your potential angular deviation.

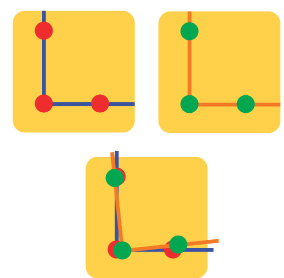


Figure 5

Avoid doing more than one device move or "leapfrog" — optimize your working volume by carefully choosing a location that will allow you to measure the most features without multiple moves.

Use the same set of references — multiple reference sets can potentially increase your error incrementally as you go from one set to the next.

Use more than three reference points — Three is the minimum number of reference points required. More points can help to better constrain features during the best fit re-alignment.

Define the reference with the same measurement device — Use the portable CMM to record the actual position of the reference points and move based on that instead of referencing to a nominal set of data that may or may not fit the actual values accurately and starts you off with the uncertainty of the device used to define them.

Conclusion

A pre-defined target grid's advantage is that the error is not likely to grow as you move the device from one location to another. With leapfrogging, this cannot be controlled and your error may or may not be compounded after two or more device moves.

Leapfrogging should be used in situations where only one device move is required. If more reach is required, then either a longer measurement arm or the use of a laser tracker is recommended.

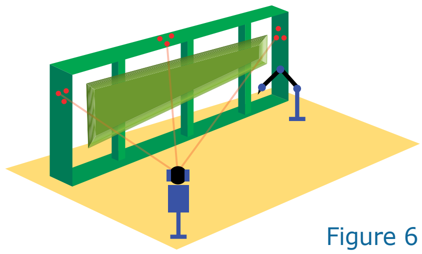


Figure 6

A FaroArm and a FARO Laser Tracker can be used to provide the same solution as the pre-defined target grid. This concept has been in use for years, especially in the aerospace industry where a Laser Tracker is used to map reference points on very large fixtures and then either FaroArms or Trackers use these target points to relocate themselves around the tool and perform more localized measurements (See figure 6). The creation of a full size grid is not necessary as long as you can set the reference points in strategic locations within a tool or work environment.

There is little advantage when using a tetrahedron over simply using three targets.

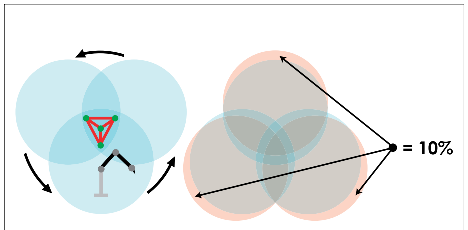


Figure 7

Assuming we use three references that are equal in size, orientation and spacing to the three spheres at the base of the tetrahedron, and that the measurement device is optimally positioned to reach all three of these; you only lose approximately 10% of the total theoretical coverage area (see figure 7). This means you effectively increase your working area by an average of 2.3 times as opposed to 2.5 with a tetrahedron. Also, you will be referencing to actual measured points instead of nominal points. This will ensure that your maximum leapfrogging — uncertainty is the same as that of the leapfrogging artifacts. Technically, you move twice, but use the best fit math to your advantage by using all the same features. If you slightly reduce the spacing between reference features you can also increase coverage by 2.5 times or better.

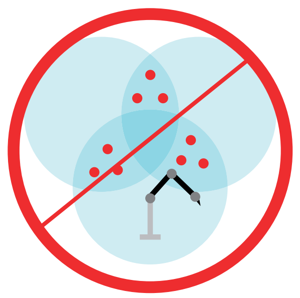


Figure 8

You would never perform this type of device relocation by using three different reference sets to avoid compounding errors. (Figure 8)

Please note that errors are estimated based on the “worst case” scenario and actual results are typically smaller.